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Towards a unified and worldwide database of surface ruptures (SURE) for Fault Displacement Hazard Analyses

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Abstract: *Fault Displacement Hazard Assessment is based on empirical relationships from historic fault ruptures. These relationships establish the likelihood of co-seismic fault displacements values, for on-fault (i.e. along the primary earthquake fault) and off-fault (i.e. distributed surface rupture off the primary rupture) displacements, for a given earthquake magnitude. These relationships are useful when trying to predict future fault displacements at, and close to an active fault, when surface rupture hazard is expected at a site (for land use planning and/or structural design of infrastructure and critical facilities located on, or close to, an active fault line). The current equations are based on sparsely populated datasets, including a limited number of mainly pre-2000 events. In 2015 an international effort started to constitute a worldwide and unified surface co-seismic displacements database (SURE) to improve further fault displacements estimations. To date, two workshops have been held and discussions on how to build such a database started. Outcomes from these discussions area: (1) the first is step should be to unify the existing datasets; and (2) the future database will include recent cases which deformation have been captured and measured with modern techniques. New parameters which are relevant to properly describe the rupture will also be required. This common effort would imply a large and open community of earthquake geologists to create a free and open access database.*

Key words*: earthquake-related hazard, surface faulting, worldwide & unified database.*

Fault Displacement Hazard Analyses (FDHA) aims to evaluate the likelihood of co-seismic surface fault displacement, for on-fault (i.e. primary/principal earthquake fault) and off-fault (i.e. distributed surface rupture off the primary rupture) displacements, for a given earthquake magnitude (Youngs et al., 2003). FDHA is based on empirical relationships from historic fault ruptures (Youngs et al., 2003; Moss and Ross, 2011; Petersen et al., 2011; Takao et al., 2013). These relationships are useful when trying to predict future fault displacements at, and close to, an active fault, when surface rupture hazard is expected at a site. In particular, these equations are useful for land use planning when new housing developments are to take place; and structural design of infrastructure and critical facilities when they have to be sited on, or close to, an active fault line (e.g.., Chen & Petersen, 2011; NRC, 2012).

To date, these relationships are based on limited information from a few historical cases and on separated datasets (Youngs et al., 2003; Moss and Ross, 2011; Petersen et al., 2011; Takao et al., 2013). Earthquake geologists and practitioners have the shared opinion that the relationships need to be updated. To date, two meetings have been held (Paris, 2015, and Menlo Park, USA, 2016) to discuss future advances on FDHA with focus on the acquisition of data and development of a worldwide, publicly available, database for surface rupture data. Two main outcomes from those discussions in terms of improvements of such a database are the need for: (1) aggregating the existing datasets; and, (2) for clearly defining the relevant parameters that should to be recorded when capturing future surface rupture data and adding it to the database.

THE AGGREGATION OF THE EXISTING DATASETS

Numerous co-seismic surface slip distributions along the seismogenic or "primary" earthquake fault exist (e.g. Lettis et al., 1997; McCalpin, 1998; Hemphill & Weldon, 1999; Wesnousky 2008; Biasi & Wesnously 2016); however, information on "distributed" faulting off the primary rupture is only available for a few earthquakes (e.g., Pezzopane & Dawson, 1996; Petersen et al., 2011; Takao et al., 2013). In both cases, the existing datasets hold limited descriptions of the ruptures, including earthquake magnitude and sense of movement, geographic coordinates and net slip of measured locations. The surface rupture database of Pezzopane & Dawson (1996) encompasses 13 normal faulting events with some distributed faulting occurrences. The strike-slip surface rupture database from Petersen et al. (2011) contains 8 events with earthquake magnitude ranging from 6.5 to 7.6. The reverse surface rupture database compiled by Moss & Ross (2011) does not include any information on distributed ruptures; however, recent studies compiled distributed rupture information to derive regressions (Inoue et al., 2016) or fault avoidance setbacks (Boncio et al., 2017). Current FDHA regressions are robust and proven useful. However, because of the scarcity of rupture information that they are based on, we stress that aggregating databases into a uniform database (so-called SURE) and improving data collection procedures is essential to produce revise empirical regressions in the short and long-term.

RELEVANT NEW PARAMETERS TO CHARACTERIZE SURFACE FAULTING

In addition to aggregating historical cases of existing datasets, modern cases should be implemented with additional information that describes comprehensively the surface rupture. Among the new parameters to be documented in the database, two of them will be included first: the geological nature of surficial layers and fault geometry complexity.

Surface Geology

The characteristic of the near surface geology influences the pattern of surface rupture, as exemplified by the 2010 El Mayor-Cucapah, Mexico earthquake (Teran et al., 2015). In this event, fault rupturing through basement rocks produced very narrowly localized deformation along discrete fault strands with each of fault plane accommodating large offsets. However, rupture through Quaternary gravels is more distributed by folding and/or discrete faulting on multiple strands with limited offsets. Sandbox models have further confirmed the importance of understanding the near surface material properties to predict the pattern and distribution of surface deformation at a study site. In those experimental results, the near-surface material stiffness is a crucial parameter that controls the rupture pattern and fabric (Stanton, 2013). In the database, we propose a basic classification (cover beds vs basement; basic sediment lithology) that can be very useful for predicting the type to rupture pattern and how deformation could be distributed at study site, as it would be easy to select examples from the database that are relevant to the study site. In the long term, specific regression for each near surface geology type may be developed.

Structural complexity

Discussions at the Paris and Menlo Park meeting highlighted the importance of understanding the structural pattern of a fault. By that we mean: whether the fault is represented by a main fault or several fault strands; whether the fault steps laterally to a different fault and/or there are gaps in the surface rupture; etc. This structural complexity influences, for example, the distributed faulting pattern. Distributed faulting does not have a uniform pattern and density along strike and is much more common at fault tips, step-overs, bends, and other geometric irregularities (e.g. 2010 EMC event: Fletcher et al., 2014; 2013 Balochistan event: Vallage et al., 2015). In very specific contexts such as compressional environments with flat and ramps, the “primary” surface rupture can be absent even for large magnitudes (e.g. 2015 M7.8 Nepal event: Grandin et al., 2015). In those cases, the main fault rupture does not reach the surface, but the surface can be deformed by folding. However, “distributed” ruptures could appear at the surface during such blind thrust earthquakes (e.g. 2004 and 2007 M6.5+ Chuetsu quakes, Japan), for instance with flexural slip or bending moment faulting.

To account for the different pattern that may appear in different types of fault segments, we propose to discretize segments in portions along the strike of historic surface ruptures. In this way, they can be analysed separately and be used to develop regression that are specific to the type of fault segment/section (e.g., step-over, fault termination, etc.)

IMPROVING THE CONTENT OF THE DATABASE: CONTRIBUTION OF NEW TECHNIQUES

Enriching the datasets

Modern techniques, such as SAR interferometry, LiDAR or SfM topography, have allowed the recognition of co-seismic deformation with much more detailed and with larger spatial extent for recent surface ruptures. For example, the geologist work was facilitated by the InSAR maps available during the early surface rupture mapping phase after the 2014 M6 Napa earthquake (DeLong et al., 2016). A large part of the moderate to small displacements could have been unnoticed by the field reconnaissance team without the support of satellite image analysis. The M5 26/3/2010 Pisayambo, Ecuador, earthquake rupture would not have ever been recognized without InSAR at all, in this remote and high-elevation region of the Andes (Champenois et al., 2017). Analysis of high resolution topographic maps derived from LiDAR imaging can provide accurate estimation of offsets, and a large amount of measured points along a fault, which is fundamental to appreciate the natural variability of surface faulting and to appropriately quantify uncertainties (Gold et al., 2013). Also, off-fault data is likely to be better detected in the recent and future events than previous ones (pre-INSAR and pre-LIDAR) thanks to these modern techniques.

It is possible that the improvement of detection capacity with modern techniques may attenuate the difference of surface rupture probability between Japan and western USA reported by Takao et al. (2013): these two active countries have very different morpho-climatic contexts that could largely have influenced the detection of historical surface rupture with classical mapping, Evidencing M5-6 earthquakes surface rupture is easier in southern California desert (e.g. Suarez-Vidal et al., 2007) than under the Japanese canopy. However, now with ALOS InSAR, subtle deformation features are measurable: see for instance the work of Fujiwara et al. (2016) who mapped distributed ruptures associated with the 2016 M7 Kumamoto earthquake under the Aso volcano forest.

Correlation of pre- and post-seismic optical images is another modern technique that has started to strongly support the acquisition of the earthquake-related deformation. This technique has been successfully applied to “historical” cases in California, demonstrating that a considerable part of co-seismic deformation was distributed off the major fault (Milliner et al., 2016). Klinger et al. (this issue) could map in detail the surface deformation associated with the 2016 M7.8 Kaikoura earthquake (NZ), using the sub-pixel correlator MicMac which provides reliable results especially in near-fault area.

Primary and distributed slip

Youngs et al. (2003) introduced two types of earthquake-related slip and derived two types of equations to calculate fault displacement hazard. Primary (or Principal) faulting is large and continuous slip, and represents movement along the main plane (or planes) that released seismic energy (Youngs et al., 2003). Distributed faulting is smaller, discontinuous slip, scattered over a wide zone, and that represents displacement on other faults in the soundings of the principal fault. Later on, Petersen et al. (2011) separated two kinds of off-fault slip: distributed (or secondary) slip which is "connected" to principal fault; and "non-connected" slip, which is triggered slip on distant faults. In their dataset, triggered slip is defined to have occurred beyond 2000 m from the main fault and the corresponding data were not included in their derived empirical regressions of off-fault slip with distance.

We propose that "triggered slip" should not be excluded from the surface displacement database. As stated by Petersen et al. 2011, "*adjacent faults are an important source of fault rupture hazard and should be considered in the analysis*". Triggered slip would however be considered separately because it responds to a different process than secondary faulting. An important issue is to objectively define triggered slip, because we argue that the distance criterion is too simplistic. This crucial step still needs to be figured out.

DATABASE STRUCTURE AND CURRENT CONTENT

The SURE database contains three sections, a "displacement observation point table"; a "fault segment table" and an "earthquake table". Displacement observation information at georeferenced points are linked to the" fault segment table" and to the causative "earthquake table" through appropriate IDs.

The displacement observation table includes basic information such as latitude, longitude, and net slip. Ideally, slip is recorded as horizontal and vertical components (with associated uncertainties), as this information will be ideal for structure design as not all faults are equally sensitive to one or other component. The table also allows for compilation of "large aperture offset", including the discrete slip on the fault trace and the inelastic part of deformation that sometimes occurs.

The fault segment table includes primary and distributed fractures (line work) and will be stored as a polyline Shapefile. Attributes for the segment file will include ID of causative earthquake. The fault segment map (geographic distribution of surface ruptures) is an important part of table as this information is used to calculate the "rupture probability" functions for the FDHA (probability of primary slip magnitude depends on distance along the primary fault; and off-fault slip depends on distance perpendicular to the main trace).

The SURE database will include a minimal level of interpretation. However, we define fields where the author's opinion (when existing) can be reported, as well as the compiler's one. The database will also include the archives of the publications, at least as an external link. The templates of the database (excel spread sheets) are available online at http://www.earthquakegeology.com/.

To date, fourty earthquakes are included in the M5-7.9 magnitude range, including 19 cases in Japan, 13 in the USA, 2 in Mexico, 1 in New Zealand, Kazakhstan, Italy, Ecuador, Turkey and Argentina; 22 strike-slip, 9 normal and normal-oblique, 8 reverse cases. Several recent cases will soon be implemented (e.g. 2014 M6 Nagano and Napa, 2016 M6.5 Norcia).

Several recent cases will be soon integrated, including the M6.5 Norcia earthquake rupture which has been extensively mapped and measured by an international team (Open EMERGEO). Observations were compiled in a homogenous way, providing a unique dataset ready to be compiled in SURE.

FUTURE STEPS

The objective is to incorporate well-known earthquake cases described in literature and to explore the post-2000 M6+ inland earthquakes that could potentially provide relevant data. A first search in the USGS earthquake database provided a catalogue of 130 shallow M6+ onshore epicentres since 2000, most having occurred in Asia (China, Iran, Japan, Russia, Pakistan, Turkey, Kyrgyzstan, Nepal, Myanmar) and very few having reported surface rupture information. There is consequently a need for participation of Asian geologists. The search for new contributors will be one major task of the SURE working group in the next years. With the PATA Days in New Zealand, we hope to gather a large number of geologists from Oceania, but also from Asia, to consolidate the SURE database network.

The US community is currently elaborating a project to prospect funding from local stakeholders; this project aims at developing a database, models, and engineering implementation guidelines for mitigation of surface faulting hazard in the western USA. The International SURE Group should clearly take advantage of this momentum and interact through collaboration and coordination of efforts with the US Community. The International community will alongside identify support and request funding for its own activities. We plan to finalize a first version of SURE by the end of 2017 which could be available on request.

We anticipate that recent events in Oceania (e.g. 2010 and 2016 events in New Zealand, as well as 2012 and 2016 Central Australia ones) will become good candidates to populate the new database, with their field and remote sensing data. On the methodological point of view, the M7.8 November 2016 Kaikoura earthquake surface rupture will provide interesting insights on the potentiality of remote sensing techniques (e.g. optical correlation) to enrich dataset, in terms of amount and quality of data.

CONCLUSION

After the starting point of the INQUA "SURFACE" project (Baize et al., 2015), two constructive workshops (Paris, 2015 and Menlo Park, 2016) were focused on the construction of the "SURE" database for FDHA. It appears that there is broad interest worldwide to update probabilistic estimates of slip distribution during future earthquakes for engineering design of infrastructures. As well as predicting the amount of surface slip at a main fault trace, distributed deformation is a key concern, particularly for structures close to active faults (e.g., pipelines, tunnels, bridges, etc.).

The current database structure has been discussed and validated by the "SURE Group" during the workshops. Worldwide researchers are currently updating and compiling existing fault rupture data that will be incorporated into the SURE database. Following the Menlo Park meeting and the project dissemination, new fault rupture data from recent earthquakes have been or will be soon provided by some of the participants, to feed the SURE database. We will seek further participation from other scientist during the PATA Days meeting in New Zealand.

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